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Thoracic Anesthesia: A Review of Current Topics and Debates

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Abstract Thoracic anesthesia is a continually evolving field due to the development of new surgical and anesthetic technologies. Advances in lung isolation techniques, ventilation strategies, and postoperative pain management have improved patient outcomes. Airway management continues to progress as different devices provide advantages and disadvantages for lung isolation, surgical visualization, and access to the operative lung. Optimal ventilation strategies are moving toward lung protection, where oxygenation and ventilation are maintained with lower, more physiologic lung volumes with judicious use of alveolar recruitment, positive end-expiratory pressure, and lower FiO_2. Neuraxial and regional anesthetics are the mainstays of postoperative analgesia, with adjuvants having roles in the acute period, but chronic post-thoracotomy pain remains challenging to treat. The role of perioperative inflammation has grown in importance, and volatile anesthetics have protective effects at the cellular and molecular levels, however the debate between the use of volatiles versus a total intravenous anesthetic technique continues.

Keywords Thoracic surgery · Lung isolation · One-lung ventilation · Continuous positive airway pressure · Positive end-expiratory pressure · Alveolar recruitment

Introduction

As in many anesthetic subspecialties, advances in thoracic anesthesia have led to direct improvements to the field of thoracic surgery and vice versa. Early in the twentieth century, thoracic surgeries were devised to treat infection and bleeding (tuberculosis, empyema, and bronchiectasis), necessitating techniques for unaffected lung protection via lung isolation [1, 2]. Currently, fewer patients are presenting with these chief complaints, and the indications for thoracic surgery have greatly expanded. We are living in a "postantibiotic era," where fewer operations are needed for infection, and now the majority are related to malignancy and end-stage lung disease; even with evolving surgical needs, lung separation techniques have remained constant [3]. As anesthetic technology and techniques have kept pace with surgical requirements, lung isolation and one-lung ventilation (OLV) techniques are being utilized more frequently to improve the operative field for cardiac, mediastinal, vascular, esophageal, and orthopedic surgeries [3, 4]. The new technologies that fostered lung separation then directly facilitated the possibility for video-assisted thoracic surgery (VATS) [1]. While the fields of thoracic anesthesiology and surgery have developed in tandem through the years, there remain several controversial topics for patient management where "best-practice" guidelines are still being debated. Herein, we offer a review of the

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field of thoracic anesthesia and highlight several of the ongoing controversies in the field.

Airway Management/Lung Isolation

Modern day thoracic surgery requires lung isolation to optimize the surgical field. In the past, there were few surgical procedures that required OLV, such as lung transplant without cardiopulmonary bypass. Absolute indications for lung isolation were based on lung protective strategies and included massive hemorrhage, infection, and lung lavage to prevent the non-diseased contralateral lung from being contaminated [4, 5]. Furthermore, OLV is indicated in bronchopleural and bronchocutaneous fistulae (or unilateral bullae), where positive pressure ventilation (PPV) would be detrimental to the diseased lung. With the expansion of VATS, OLV for surgical indications has become the norm, where lung collapse is necessary because the operative field is small, and optimal visualization is critical for surgical success [2, 5].

There are multiple strategies that can be used to achieve lung isolation and OLV. Equipment that can facilitate this specialized technique includes double-lumen endobronchial tubes (DLTs), bronchial blockers (BBs), and single-lumen endotracheal tubes (SLTs). While there are many different brands of each device, the main principles of each are the same. DLTs are made up of two color-coded tubes connected side-by-side (one endotracheal lumen and one endobronchial lumen) that can be fitted as either right- or left-sided. BBs are essentially balloons mounted on hollow bore wands that can be positioned to occlude one of the mainstem bronchi and facilitate collapse of the ipsilateral lung. If full lung collapse is not tolerated, BBs can also be placed more distal to the mainstem bronchus to obtain segmental collapse of the lung [6]. The main BBs on the market today include the Arndt, Cohen, Fuji Univent/Uniblocker, and Rusch EZ-Blocker (Fig. 1). If neither of these modalities are available, a standard SLT may be placed directly into the mainstem bronchus of the non-diseased contralateral lung [3, 4, 7••]. Currently, there is no universal agreement as to which technique is best overall, but a review of the literature can shed light on instances where one device may be preferable to another (Table 1).

Time for Placement/Ease of Positioning

Multiple prospective randomized controlled trials (RCTs) compared DLTs to BBs with regard to time to placement and likelihood of malposition. The results are mixed; some studies demonstrate no difference between the time required for placement [8–11], while other studies show that more time is needed for proper positioning of BBs [12–15]. More specifically, studies illustrate that additional time is necessary for placement of left BBs in comparison to both right BBs or DLTs [16]. With regard to malpositioning of the tube, again some studies found no difference in the number of malpositions [9, 11, 17], whereas others indicated that BBs are more likely to be placed incorrectly [8, 12, 14, 15]. The majority of malpositions took place when the patient was moved to the lateral decubitus position and not on initial placement [12]. A recent meta-analysis combined the data from these RCTs and concluded that DLTs can be placed faster (mean difference 51 s) and are more likely to be positioned properly as compared to BBs. While this difference may be statistically significant, 51 s is likely not a clinically relevant amount of time [7••]. Furthermore, additional time may be needed at the end of the procedure if a DLT is placed and tube exchange is required for postoperative mechanical ventilation [7••, 8, 10, 11, 14, 15, 17, 18]. One RCT that examined the effect of the anesthesiologist's experience on successful placement of DLTs versus BBs discovered that the limiting factor for successful placement of both devices was the anesthesiologist's inexperience with lung isolation and "unfamiliarity" with tracheobronchial anatomy [19].

Quality of Lung Deflation and Surgical Exposure/Ability to Apply Suction and CPAP

While there are some studies showing equivalence between the equipment in regards to lung deflation and surgical exposure [8, 9, 11, 12, 14, 15, 17], there are several studies that specifically favor DLTs [10, 20]. In some instances, BBs required more time [21] or the application of suction [12, 17, 20] to achieve full lung collapse. It should be noted however that operating conditions were rated similarly once deflation was attained [20]. One study found that lung deflation was superior with the use of left BBs and DLTs compared to the right BBs due to incomplete obstruction of the right mainstem bronchus even with full inflation of the cuff and occlusion of the RUL bronchus [16]. After the results of these studies were compiled in the meta-analysis, it was determined ultimately that there is "no significant difference in the quality of lung collapse between DLTs and BBs" [7••].

While collapse of the lung may be equivalent, DLTs are superior for suctioning of blood and infectious materials (since the BBs have smaller lumens) [4, 7••] and CPAP can more easily be applied to the wider lumen of a DLT as compared to a BB [4, 6].

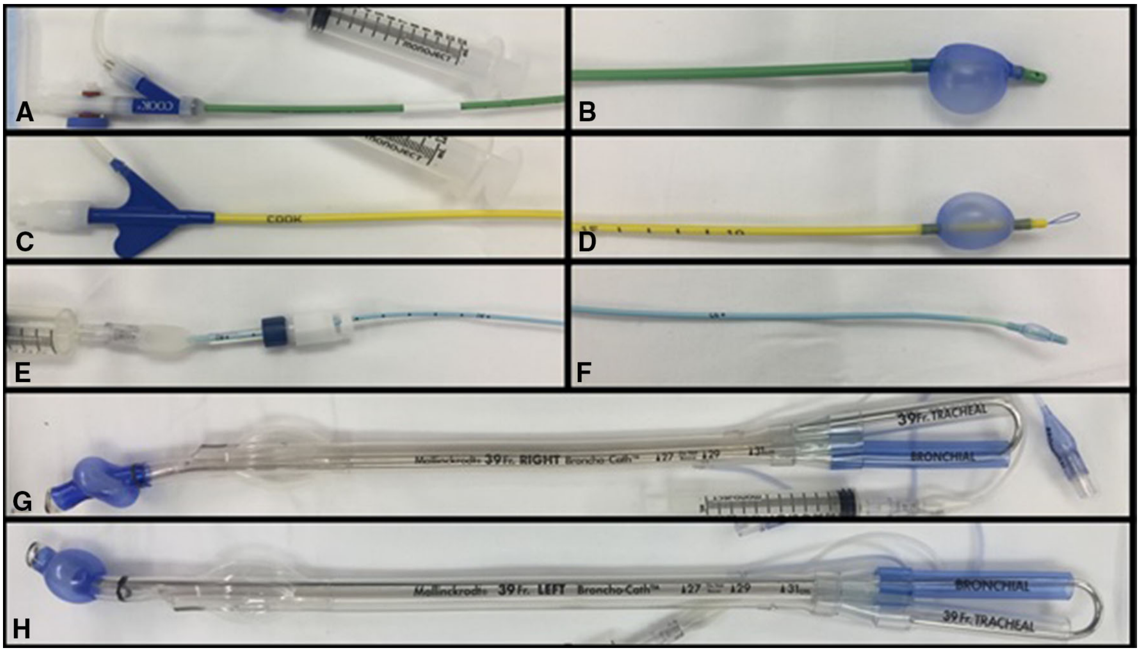

Fig. 1 Double-lumen endobronchial tubes and bronchial blockers. From *top* to *bottom* **a**, **b** Cohen endobronchial blocker, 9 Fr; **c**, **d** Arndt Endobronchial Blocker, 9 Fr; **e**, **f** Fuji endotracheal tube uniblocker, 5 Fr; **g** Mallinckrodt right endobronchial tube, 39 Fr; **h** Mallinckrodt left endobronchial tube, 39 Fr

Table 1 Indications for use of double-lumen endobronchial tubes versus bronchial blockers

Double-lumen endobronchial tubes	Bronchial blockers
Lung isolation in the presence of significant bleeding or infection	Abnormal anatomy
Easier application of suction and CPAP	Difficult airway
Extensive pulmonary toilet	Tracheostomy
Mainstem bronchial disease or sleeve resection	Pediatrics
Bilateral procedures (e.g., double-lung transplant or bilateral sympathectomy)	Risk of aspiration
	Need for postoperative mechanical ventilation
	Selective lobar blockade

Adverse Effects

While the DLTs have been shown to be superior insofar as they facilitate easy application of suction and CPAP, and they are faster to place with fewer malpositions, there are some drawbacks. Four of the 13 studies in the meta-analysis collected data on sore throat and hoarseness. Three of these studies found an increase in these adverse events with the use of DLTs compared to BBs [11, 20, 21], while the fourth study noted no difference [14]. When the results were compiled in the meta-analysis, there was a statistically significant increase in incidence of sore throat and hoarseness with DLTs compared to BBs [7]. Three of the RCTs demonstrated that DLTs were associated with a statistically significant increase in airway injury (including vocal cord, tracheal, and bronchial erythema, edema, hematoma, and granuloma) compared to BBs [7, 11, 20, 21].

DLTs are much larger than SLTs in external diameter. A popular older study demonstrated that larger endotracheal tube size is correlated with increasing occurrence and severity of postoperative sore throat and hoarseness [22]. Furthermore, there are case reports of bronchial and tracheobronchial rupture associated with DLTs [23–27]. It is possible that the larger size and greater stiffness of the DLTs are responsible for the higher incidence of adverse effects [7••]. It remains to be elucidated whether the use of BBs can decrease the occurrence of these severe complications [20].

DLTs also have the disadvantage of requiring multiple laryngoscopies when postoperative mechanical ventilation is needed, and the DLT needs to be exchanged for an SLT at the end of the procedure. Patients with abnormal anatomy or difficult airways may benefit from the use of a BB and single laryngoscopy. Cost is another consideration, with DLTs being less expensive [7••, 8, 9, 12].

While DLTs and BBs may provide equivalent surgical exposure, each tube does demonstrate superiority in certain clinical situations. DLTs allow for faster placement, which may be negated by the need for tube exchange in a patient requiring mechanical ventilation postoperatively. DLTs are also associated with airway trauma. They do confer the advantage of access to the operative lung for application of both suction and CPAP. BBs may take slightly longer to place, and may be more likely to be malpositioned, however there is a lower incidence of airway trauma. Additionally, BBs are more appropriate in the difficult airway and for patients with abnormal anatomy. Given that the literature supports both sides, it behooves the anesthesiologist to be proficient in placement of both devices and understand the indications for one over the other.

Ventilation Strategies for Thoracic Surgery

Thoracic surgery presents a unique challenge to the anesthesiologist because it involves OLV, via the isolation techniques described above. For most of its history, the biggest challenge of OLV was hypoxemia [38, 39]. Prevailing thought was to increase minute ventilation of the dependent lung through larger tidal volumes (sometimes upwards of 10–12 mL/kg) to account for the loss of lung tissue participating in ventilation. Furthermore, this strategy was applied without application of positive end-expiratory pressure (PEEP). A fraction of inspired oxygen (FiO_2) of 100 % was routinely employed not just as an intervention for transient hypoxemia but as a standard of treatment [28]. Since that time, multiple changes in the safety of thoracic surgery and our understanding of lung pathophysiology have put the spotlight on the anesthetic management of thoracic patients as a possible source of lung injury. While surgical mortality has decreased, acute lung injury rates have stayed the same. Current opinion implicates ventilation strategies and fluid administration as likely culprits [29, 30]. Consequently, a more refined approach to OLV is indicated to treat hypoxemia, while also minimizing lung injury from hyperinflation and hyperoxia.

Ideal Lung Volumes

In 1963, Tenney and Remmers described an elegant experiment defining mammalian lung tidal volume as 6.3 mL/kg of ideal body weight [31]. Acknowledging what we know now about acute respiratory distress syndrome (ARDS) and acute lung injury (ALI), larger than physiologic tidal volumes should be contraindicated in most patients, owing to the damage that can be observed from V/Q mismatch, hyperperfusion, and alveolar damage [32].

Many studies have examined the harm of large tidal volumes and the benefit of protective lung volumes. One study looked at 120 patients randomized to receive OLV with either 10 mL/kg tidal volumes [with or without alveolar recruitment strategies (ARS)] versus a group receiving 6 mL/kg tidal volumes and 8 cm H_2O of PEEP (with or without ARS). The lower lung volume group performed better in measures of arterial oxygenation and lung injury [33]. In another study, 40 patients were randomized to either receive high tidal volume or protective lung volume ventilation in OLV. The protective lung volume group not only had lower airway pressures and resistance, but had lower levels of IL-6 and IL-8, important inflammatory markers. This suggests that the pro-inflammatory state of OLV may be ameliorated by similar ventilation strategies as those used in ARDS [34].

While the preponderance of evidence supports the use of smaller, protective tidal volumes in OLV, Maslow et al. demonstrated in a study of 34 patients that using high volumes of 10–12 mL/kg did not result in increased morbidity, and in fact had less hypercarbia, less dead space ventilation, better dynamic compliance, and less postoperative atelectasis. The authors argued that in patients without existing lung injury, low tidal volumes confer no mortality benefit and come at a cost, and that high tidal volumes can be given safely in compliant lungs [35•]. While their measures were statistically significant, the findings fly in the face of other studies that demonstrated clinically relevant differences in outcomes, histologic findings of barotrauma, and biological markers of inflammation between ventilation strategies. A large review by Schultz et al. recommends lower tidal volumes in patients without ALI/ARDS given the number of studies demonstrating either direct clinical impacts (pulmonary function) or proxy markers (inflammatory signals, histological findings), showing decreased injury from low tidal volume strategies [36]. Further review of the literature repeatedly demonstrates the benefit of lower tidal volumes during OLV [37–39, 40••]. So, while Maslow's group illustrated the potential benefits of high tidal volume ventilation, we caution the use of this strategy as the majority of evidence in recent literature still refutes this technique.

Fraction Inspired Oxygen (FiO_2)

Another controversial issue in the field is the appropriate oxygen concentration that should be delivered to the patient. Using high levels of inspired oxygen does more than just treat hypoxemia. It might also improve wound healing [39], strengthen immune function [41], decrease nausea, and increase pulmonary blood flow to the dependent lung [29]. However, supraoxygenation is not without cost. Persistently elevated oxygen concentration may cause atelectasis through reabsorption, which itself is injurious through atelectrauma (the cyclic recruitment and collapse of alveoli, which may lead to dysfunction of surfactant) [42]. This alone could be reason enough to pursue lower FiO_2 strategies as part of a multimodal approach in improving oxygenation through optimal lung mechanics; however the implications of hyperoxia on lung injury are perhaps the most compelling. Lung tissue already injured by surgical manipulation (and the resulting edema and re-expansion) is further injured by pro-oxidant forces in the setting of hyperoxia [43]. Furthermore, reperfusion injury in one lung can induce ALI in the other [44]. In one study, 20 patients undergoing OLV for VATS sustained "massive superoxide production" during reperfusion following OLV which would further support the restrictive use of oxygen [45]. OLV in and of itself is thought to contribute to oxidative stress and may be a potential cause for cardiovascular complications. One study examining 132 patients with lung cancer after lobectomies experienced elevated levels of malondialdehyde (a marker of oxidative stress), as well as increased incidence of respiratory failure, cardiac arrhythmias, and pulmonary hypertension [46].

While no definitive rule exists, the optimal oxygenation goals for OLV should likely be for $SpO_2 > 90$, with FiO_2 between 30 and 50 % according to some sources [29].

Continuous Positive Airway Pressure (CPAP)

CPAP has been utilized in OLV as a means of improving arterial oxygenation when otherwise limited by the mechanics and blood flow in the dependent, ventilated lung [47]. Methods have been described on how to apply CPAP to the operative lung, even to specific lobar segments [48, 49]. Given at low pressures, CPAP can improve oxygenation without interfering with the surgical field in open thoracotomy; however its role in VATS is controversial as even minor inflation can disrupt the surgeon. Studying 20 patients, Kim et al. found that applying CPAP at 6 cm H_20 improved oxygenation without obstructing the surgical field, however at 9 cm H_2O, 90 % of surgical fields were obstructed [50]. It is interesting to note that in this study, minute ventilation of the dependent lung was maintained with 10 mL/kg tidal volumes, which is much larger than the tidal volumes of prevailing lung protective ventilation strategies, and furthermore no mention of PEEP is made. CPAP may also have the benefit of allowing for decreased intraoperative FiO_2 requirements. However, given the technical aspects of applying CPAP, the newer data supporting low tidal volume ventilation with ARS and PEEP, and the increasing utilization of VATS for larger procedures, CPAP may be better relegated as an intervention for hypoxemia and not as a standard ventilation strategy.

Positive End-Expiratory Pressure (PEEP) and Alveolar Recruitment Strategies (ARS)

Delivering lower tidal volumes can increase atelectasis, which not only affects oxygenation, but can injure the lung through the cyclical collapse of alveoli between breaths [39]. Adding PEEP keeps the alveoli open, minimizing atelectrauma [32]. PEEP must be used judiciously however, as it can actually impede oxygenation of blood through over-distension of alveoli. Therefore, PEEP may be most valuable when individualized to the patient's compliance curve [30]. Ferrando et al. studied 30 patients, and using a PEEP decrement trial were able to optimize static compliance and arterial oxygenation through individualized PEEP and recruitment maneuvers [51].

ARS also play an important role in OLV. Positioning, shift of mediastinal contents, a relaxed diaphragm under anesthesia, PPV, and pneumothorax of the operative hemithorax all lead to decreased FRC and subsequent decreased compliance of the dependent ventilated lung [37]. In the patient with existing atelectasis from lateral positioning and relaxation of the diaphragm under anesthesia, adding recruitment maneuvers before and during OLV may be indicated. Unzueta performed an RCT in which the experimental group received a recruitment strategy (consisting of 10 consecutive breaths at a plateau pressure of 40 cm H_2O with 20 cm H_2O PEEP applied immediately before and after OLV) and were found to have improved alveolar dead space ratios as well as arterial oxygenation and efficiency of ventilation [52]. These findings confirm earlier studies [53, 54].

Ventilation during thoracic surgery should be focused on reducing trauma to the lungs by using lower FiO_2, physiologic tidal volumes, ARS, and PEEP. This will not only improve oxygenation, but decrease alveolar damage, inflammation, and the associated postoperative pulmonary complications. Given improvement in surgical mortality but continued postoperative lung complications, it is critical for the anesthesiologist to be well versed in current lung protective strategies, ventilation management techniques, and postoperative pain control in an attempt to reduce postoperative complications.

Pain and Inflammation

A discussion of thoracic anesthesia would not be complete without mentioning the continuing debates about analgesic techniques and volatile versus intravenous anesthetics.

Multiple modalities exist for treating postoperative pain, including regional anesthesia and adjuvants (Table 2). Thoracic epidural analgesia (TEA) continues to be a well-supported approach, providing advantages over paravertebral blocks in terms of area of effect, proficiency of anesthesiologists, and ability to perform without ultrasound [55••]. Multiple adjuvants appear to help with acute pain, such as preemptive TEA, ketamine, and alpha-2 agonists; however chronic post-thoracotomy pain (CPTP) continues to be a challenge [56–58]. Several risk factors for developing CPTP have been found, including severe postoperative pain, pre-operative anxiety, and female sex [56, 59]. Inflammation is thought to play a role in the development of CPTP as lung transplant recipients, who have similarly undergone thoracotomy, but are subsequently placed on immunosuppressants, show decreased incidence of CPTP [60].

While non-transplant thoracotomy patients are not suitable candidates for immunosuppression purely for its anti-inflammatory effects, consideration of inflammation from the anesthetic is worth discussion. The inflammatory effect of PPV has already been discussed above, and applies as well to thoracoscopic procedures [61]. This inflammation also occurs as a consequence of reperfusion injury from surgically induced ischemia of the lung [62]. Some research indicates that volatile anesthetics like isoflurane and desflurane may have protective benefits over propofol with regard to local inflammation in the lung parenchyma [63, 64]. In vivo studies of animals have demonstrated this effect at the endothelial glycocalyx, essential for protecting against ischemia–reperfusion injury [65–67]. Given the similarities between inflammation caused by OLV and ARDS, and the role of inflammation in these processes [40••], further studies on reducing the biotrauma of an anesthetic are warranted.

Table 2 Postoperative analgesic techniques and adjuvants for thoracic surgery

Post-thoracotomy analgesic techniques	Adjuvants
Thoracic epidural analgesia	Clonidine
Thoracic paravertebral block	Dexmedetomidine
Intrathecal opioid analgesia	Ketamine
Continuous wound catheter	Traditional NSAIDs
Transcutaneous electrical nerve stimulation	COX-2 Inhibitors
Cryoanalgesia	Gabapentin
TIVA (remifentanil and propofol)	
GETA with sevoflurane	

Conclusion

Thoracic anesthesia continues to be an evolving subspecialty, and it is this evolution that provides thoracic surgeons the ability to deliver innovative surgical techniques that contribute to improved patient safety, satisfaction, and outcome. While much progress has been made, there is still much work to accomplish in terms of intraoperative management. This includes refining ideal ventilation and oxygenation strategies that minimize lung injury in patients with preexisting lung disease, and tailoring postoperative pain management to improve recovery and reduce complications.

Compliance with Ethics Guidelines

Conflict of Interest Nicolette Schlichting, Kenneth Flax, Adam Levine, Samuel DeMaria, Jr., and Andrew Goldberg declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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•• Of major importance

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